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13. ABSTRACT (Maximum 200 words)

The report describes summary results of a community-wide assessment of our understanding of the structure and dynamics of turbulent boundary layers. It also summarizes the findings of an in depth numerical study of vortex structures in the boundary layer.

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FINAL REPORT

AFOSR GRANT 91-0364

SUBMITTED BY

THERMOSCIENCES DIVISION

DEPARTMENT OF MECHANICAL ENGINEERING

STANFORD UNIVERSITY

PRINCIPAL INVESTIGATOR

S. J. KLINE

MARCH 31, 1993

PURPOSE OF THE WORK:

The goal of this work was to further illuminate the processes of turbulence production and dissipation near solid boundaries with particular emphasis on the role of vortices in the boundary layer.

HISTORICAL BACKGROUND:

Work in this area has been continued since the mid-1950's largely under AFOSR sponsorship. A paper published from this work in 1967 has become a citation classic. Another paper published in 1971 has been the basis for much further research in many laboratories. Up until about 1980 the only means for study in this area was experiments, and many of the most instructive experiments has used the combined time-streakline hydrogen bubble wires developed within earlier work under AFOSR sponsorship.

In the 1980's numerical solutions of the complete Navier Stokes equations became possible in the supercomputers, and a number of simple paradigmatic flows were computed and the results stored on disk. These DNS data bases are more complete in several ways than results which can be obtained in the laboratory, and led to a new vein of investigation..

Following this lead, S. K. Robinson with S. J. Kline investigated the data base for the flat plate created by Phillipe Spalart at NASA Ames Research Center. This work led to an improved and more complete picture of the physics of the boundary layer, and led to a number of publications (see references). The most complete report of this work is published in NASA TM 103859 "The Kinematics of Turbulent Boundary Layer Structure by S. K. Robinson, April, 1991.

Robinson's work led to a citation in NASA achievements and a NASA prize. Robinson has since been made a Division Head at NASA Langley Research Center.

Robinson's work established far more clearly than before the central role of two types of vortices in the boundary layer. The work provided a picture of the kinematics, but not the dynamics of these vortex structures. Also the method used for vortex identification by Robinson was an order of magnitude better than any prior method, but was not based on a fundamental definition of a vortex.

PROJECT GOALS:

As a continuation of the work of Robinson, reported above, the project reported here undertook four tasks:

(i) Provide a fundamental definition of a vortex;

(ii) Create computer software based on the fundamental definition which will identify vortices both in planes and three dimensions in the DNS data bases;

(iii) Document the nature of vortices in the boundary layer for a large enough sample to provide good statistics;

(iv) Study the relation of the vortices to turbulence production and dissipation, to the other known structures in the turbulent boundary layer.

PROJECT ACCOMPLISHMENTS

At 31 January, 1993, the end of this Grant, goals (i), (ii) and (iii) had been completely fulfilled, and work on goal (iv) was well advanced. A brief summary of new results follows.

The vortices in the boundary layer are mostly of an "open type" in the sense that they do not have closed streamlines. The structure of the vortices can be understood as having three regions (inner, middle and outer): (a) the inner region is viscous core essentially like the core of classical viscous vortex theory; (b) the middle region has closed streamlines and a velocity distribution like that of an Oseen Vortex; (c) the outer region has streamlines which thread away from the vortex and connect with other elements in the flow.

As a result of the picture given in the prior paragraph, the vortices can be seen as wrapping (or unwrapping) shear layers. An important result is that the regions of high Reynolds stress in the boundary layer are associated with the regions where vortex outer regions are wrapping and unwrapping and not with the inner or middle portion of the vortices. Statistics on this matter are being gathered.

Vortices occur with both senses of rotation, that of the mean strain and the opposite and also can be either wrapping up or unwrapping shear layers. Distributions of all four types as functions of y^+ are being prepared.

An explicit summary of these results is attached as Appendix I. Appendix I is a detailed dissertation proposal by L. Portela, and indicates the current state of the work and proposed dates of completion.

An entirely different form of work also on boundary layer physics has also been started under the current grant. This is called "A Ringi For Boundary Layer Structure." The idea is that the results of what we know collectively are stated and circulated on a cyclic basis through the research community so that they reach each worker once per year. The individual researcher can add, comment, question results etc. as he/she sees fit. Comments will be attached and/or integrated by the editor, currently S. J. Kline. For example in a paper at the recent meeting for W. C. Reynolds 60th birthday, W. George of Buffalo, presented results challenging part of the accepted wisdom about the mean profiles

in the outer part of the layer. These results will be incorporated in the Ringi (since the editor believe George's comments are correct). Other suggestions by such workers as F. Hussain, C. R. Smith and R. Blackwelder have been received and will be incorporated in the future drafts.

The suggestion for the "Ringi" has been well received by the community. 55 Researchers are actively participating and 15 more have asked to be kept informed. We believe this mode of communication is a particularly suitable one for boundary layer structure because the details are too complex for good communication within the times normally allotted in technical meetings and because there has been difficulty in the past in reaching consensus on a number of points.

PUBLICATION OF THE RESULTS AND FUTURE WORK:

We expect to complete a dissertation and report of the work of Portela in 1993, and will prepare journal papers in the usual way.

In addition, Mr. Juan Chacin will continue the work to investigate other flows since Mr. Portela's work will only study the flat plate layer. Mr. Chacin and Mr. Portela are preparing the software for transmission and use in the Flow Physics Division at NASA Langley Research Center under the direction of S. K. Robinson. Mr. Chacin's work will be financed by this NASA Division.

A FINAL REMARK:

AFOSR has been supporting this work under this and related earlier contracts since the late 1950's. Since the principal investigator has retired, he does not plan further proposals to AFSOR. It is thus appropriate to express the thanks of both the Principal Investigator and the Thermosciences Division for this long-continued support.

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APPENDIX I

Identification and Characterization of Vortices in the Turbulent Boundary Layer

L.M. Portela

March 10, 1993

The dissertation deals with the identification of vortices , their characterization in the turbulent boundary layer and their relation with: the Reynolds stresses turbulence production, and dissipation.

The techniques developed are applied to the DNS data base of Spalart thus obtaining a characterization of the vortices in the flat plate turbulent boundary layer.

The dissertation will consist of five major parts.

1 Definition and Identification of Vortices

The issues of a proper definition of a vortex and of the inadequacy of the existing methods of identification, including:

- An adequate definition of a vortex
- The identification of vortices and the inadequacy of the existing methods
- The several reasons why vortices must be distinguished from vorticity lines and vorticity tubes

Schedule

This part is basically done ($\approx 95\%$), and some of the major writing regarding it was done as part of a paper to be submited to JFM (paper 1): *The vortex concept and its identification in turbulent boundary layer flows.* This paper will also contain the results of parts two, three and four regarding 2D vortices (both streamwise and spanwise). A first draft has already been done, and we expect to have a final version by May 93.

2 Characterization of Vortices

Deals with the classification of vortices according to their geometric, kinematic and dynamic characteristics:

- Geometric
  - axis orientation (streamwise, spanwise, 3D structure)
  - size and the different regions of the vortex (center, middle region, outer region)
  - open and closed
  - wrapping and unwrapping
- Kinematic
  - circulation (direction and intensity)
  - velocity distibution
  - vorticity distribution
- Dynamic
  - pressure defect
  - Reynolds stresses distribution

This part discusses: the connection between the different aspects of the characterization; their relations with the definition and identification of vortices; their importance for understanding the interaction of the vortices with the flow and their effects (both the interaction between vortices and the interaction of vortices with other structures).

Schedule

Most of this part is done ($\approx 90\%$). Some carefull organization of the ideas and writing still needs to be done. Most of it will be done as part of preparation of paper 1.

3 Software for Vortex Identification and Characterization

Deals with the algorithms and numerical means for the identification and characterization of vortices and its implementation. This part provides software for:

- Identification of the center of the vortex
- Identification of the particles of the vortex
- Identification of the axis of the vortex (3D)
- Characterization of the vortex

Schedule

The software of the identification of the center of the vortex and of the particles of the vortex is done and in use.

The software for the identification of the axis of the vortex is basically done ($\approx 80\%$), and some results were already obtained (presented in a seminar last May). Some work is still needed to obtain a more general program. Also, some carefull organization of the ideas and writing regarding 3D identification is still needed. This will be done as part of a paper about 3D identification and 3D results (paper 2): *The identification and characterization of three-dimensional vortical structures in turbulent boundary layer flows.* We expect to have a first draft by July 93.

The software for the characterization of the vortex is basically done ($\approx 80\%$). Some work is still needed to identify regions belonging simultaneously to different vortices, which is needed for part five. This will be done as the work on part five progresses.

4 Vortices in the Flat Plate Turbulent Boundary Layer

Deals with the application of the concepts and software developed to the flat plate boundary layer, using the DNS data base of Spalart.

The vortices are classified as a function of y+, according to the characterization discussed in part two, using the algorithms and software presented

in part three. The meaningful pdf's of the several characteristics are presented, together with the major conclusions and findings (e.g., log-normal pdf's, diameter following mixing-length behavior, vortices with rotation contrary to the mean strain, etc.). Some speculations based on these results are explored.

Schedule

Most of the results have already been obtained ($\approx 80\%$), except the part related to the several regions and the improved definition of size. However, the results were obtained just for one time step and half of Spalart's total volume ($\Delta x+ \approx 2450$, $\Delta y+ \approx 1100$, $\Delta z+ \approx 1225$), at $Re_\theta = 670$, due to the limited computer resources that were available.

With the new computer resources available, starting March 93, we plan to run the software for a complete volume and several time steps. This will allow a much bigger sample and, consequently, much more meaningfull statistical results.

If possible (we will consult Spalart) we would like to run the software also for $Re_\theta = 1410$ and compare the results from the two Reynolds numbers. If time permits, this comparison will be presented in paper 3: *The Reynolds number effect on the characteristics of vortices in the turbulent boundary layer.*

In any event, the results already obtained for $Re_\theta = 670$ will be presented as part of paper 1. A more complete set of data might be reserved for a later paper (paper 3), depending on their availability at the time of finishing paper 1.

5 The Relation Between Vortices and Turbulence Characteristics

Deals with the relation between vortices and the turbulence characteristics in the flat plate boundary layer (Reynolds stresses, turbulence production and dissipation). It uses the DNS data base of Spalart.

The characterization of vortices developed provides a very natural and meaningful basis for understanding the relation between the vortices and the turbulence characteristics of the flow. In particular, the separation of each vortex into different regions provides a mean of relating the location of the regions of high turbulence activity with respect to nearby vortices. This

indicates how the interaction between the vortices and the flow (interaction with other vortices and with other structures) occurs. The results already obtained show:

- High Reynolds stresses and turbulence production are concentrated in a small portion of the volume of the boundary layer. These *High Reynolds Stresses Volumes* (HRSV) are responsible for most of the turbulence production in the boundary layer.

- Exponential type of behavior for both the Reynolds stresses and the production of turbulent kinetic energy as a function of volume when sorted in increasing order. More than 90% of the production ocurring in less than 30% of the volume (preliminary figures)

- The HRSV are associated with the vortices and their characterization, more particulary, the separation of the vortex in different regions provides a natural way of identifying and understanding the HRSV

- The outer region of the vortices is often a region of interaction of the vortices with the rest of the flow (with other vortices and structures), with HRSV

The complete results will include:

- Distribution of the Reynolds stresses and production of turbulent kinetic energy in the boundary layer, sorted in increasing order by volume

- Statistics of the total production of turbulent kinetic energy and of the HRSV (percentage located in the different regions of the vortex and in the regions affected by several vortices)

- Distribution of the Reynolds sresses and production of turbulent kinetic energy in the different regions of the vortex

The results will be delineated as a function of y+, segregated according to the different types of vortices (as discussed in part two), and according to the type of Reynolds stresses (positive, negative and by quadrants). Implications of these results will be explored.

The results obtained for the Reynolds stresses and turbulence production will be repeated for the turbulence dissipation (this is a very trivial

and straightforward procedure, once the characterization of the vortices in different regions has been made). This will provide a more complete picture of the relation between the vortices and the dynamics of the turbulence in the boundary layer.

Schedule

Some of the results regarding the Reynolds sresses and turbulence production are already done. However, some software for its completion still needs to be done and a complete set of data needs to be taken. Regarding turbulence production and Reynolds stresses we estimate that roughly 50% of the work is done. The results for the dissipation still need to be obtained. We estimate to finish by September 93, together with a paper (paper 4): *The relation between vortices and the turbulence characteristics in the boundary layer.*

List of Papers

1. The vortex concept and its identification in turbulent boundary layer flows
2. The identification and characterization of three-dimensional vortical structures in turbulent boundary layer flows
3. The Reynolds number effect on the characteristics of vortices in the turbulent boundary layer
4. The relation between vortices and the turbulence characteristics in the boundary layer